



## MyWindTurbine – Energy Yield Calculations

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*Publication date:*  
2016

*Document Version*  
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

*Citation (APA):*  
Bechmann, A., Conti, D., Davis, N., Hansen, B. O., Kelly, M. C., Mortensen, N. G., Nielsen, M., Badger, J., & Pena Diaz, A. (2016). *MyWindTurbine – Energy Yield Calculations*. DTU Wind Energy. DTU Wind Energy E No. 0132

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# MyWindTurbine – Energy Yield Calculations

DTU Vindenergi  
E Rapport 2016

Andreas Bechmann, Davide Conti, Neil Davis, Brian O. Hansen, Mark C. Kelly, Niels G. Mortensen, Morten Nielsen, Jake Badger, Alfredo Peña

DTU Wind Energy E-0132 (EN)

October 2016

**DTU Vindenergi**  
Institut for Vindenergi

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**Abstract (max. 2000 char.):**

This report documents part of the work done by work package 7 “test and validation” of the “Online WAsP” project funded by the Danish Energy Technology and Demonstration Program (EUDP). The purpose of the report is to evaluate the “calculation engine” of [www.myWindTurbine.com](http://www.myWindTurbine.com). For the validation, energy yield calculations from myWT are compared to production data from 20 different small size wind turbine generators in Denmark. The results give an indication of the energy yield calculation uncertainty of myWT.

**DTU Wind Energy E-0132 (EN)**  
**October 2016**

**ISSN:**

**ISBN:**

978-87-93278-98-1

**Project no:**

DTU Wind Energy 43208

**Sponsorship:**

EUDP 64013-0512

**Cover:**

**Pages:** 30

**Tables:** 2

**Figures:** 7

**References:** 10

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# 1. Background

This report documents part of the work done by work package 7 “test and validation” of the “Online WAsP” project funded by the Danish Energy Technology and Demonstration Program (EUDP). The purpose of the report is to evaluate the “calculation engine” of [www.myWindTurbine.com](http://www.myWindTurbine.com) (myWT). For the validation, energy yield calculations from myWT are compared to production datasets from 20 different small size wind turbine generators (SWT) in Denmark. The results give an indication of the energy yield calculation uncertainty of myWT.

The calculations presented in this report are carried out for wind turbines located in Denmark only. One reason for this is due to the access to high-quality energy production datasets and SWT power curves provided by Danish manufacturers needed for accurate model comparisons. In this report, the source of the data is anonymized, but data provided by the Danish wind turbine manufacturers “Thy møllen” ([www.thymoellen.dk](http://www.thymoellen.dk)), “HS Wind” ([www.hswind.dk](http://www.hswind.dk)) and “Gaia-Wind” ([www.gaia-wind.com](http://www.gaia-wind.com)) is used. Denmark has also been chosen due to the availability of the Danish Wind Energy Index (DK Index) ([www.vindstat.dk](http://www.vindstat.dk)) dating back to 1979. The index compares the monthly energy productions from some wind turbines to the long-term monthly average of the same turbines. Using the DK Index, the production dataset provided by the SWT manufacturers can be “long-term adjusted.” Since the energy production of wind turbines changes a lot from year to year, it is necessary with long-term adjustments to compare with the 20-year mean annual energy production (AEP) calculated by myWT; the DK Index allow for this.

In addition to having good production data to evaluate myWT, the background data used for the myWT (at the time of this report) is of higher quality in Denmark than for the rest of the world. For one, a dataset for all obstacles (trees, buildings, hedges, etc.) is included in the Danish dataset (also in the UK), whereas these need to be added manually by the myWT user for the sites located outside of Denmark and the UK. It is, therefore, easier to do a large-scale validation for Denmark. myWT works for the whole world. However, the accuracy of the energy yield calculations (at the time of the report) is expected to be slightly higher in Denmark. Therefore, this report documents the accuracy in Denmark and as the background data of myWT gradually improves similar accuracy is expected globally.

The SWTs used in this report have wingtip heights of 25 m, typically with a generator size of around 10 kW or a little larger. They are freestanding, mounted on a tower placed in a relatively open country site, but often within 20 m of a farm house. Graphics of the environment of each SWT used is found in the appendix. None of the turbines are building-mounted or located in an urban environment. The findings in this report are therefore not valid for SWTs installed in such locations. A report that analyses the performance of building mounted micro wind turbines was made in the Warwick Trials Project (Encraft, 2009).

## 2. Introduction

DTU Wind Energy (DTU) has, for the past 25 years, developed and distributed the WAsP software (Wind Atlas Analysis and Application Program), used for wind resource assessment calculations by thousands of wind energy professionals all over the world. WindPRO is a software package developed by EMD International A/S (EMD) for designing, planning, and documenting wind turbine projects. For a wind energy project developer, the comprehensive studies provided by WAsP and windPRO are expensive regarding infrastructure investment and human resources but represent a minor cost in the total investment of large-scale wind energy projects.

For SWTs, a thorough assessment of the potential energy yield is important when establishing the feasibility and profitability of a new wind energy project and ensuring successful operation. However, given the lower investment and returns of SWT projects, WAsP and windPRO analyses are often considered too costly. Moreover, the proper use of WAsP and windPRO requires experience and insight in wind energy meteorology, local on-site wind measurements, and environmental impact assessment. Based on these considerations, the aim of the Online WAsP project (see myWT, 2016) was to develop a low-cost and user-friendly online tool targeted for SWTs. The name of the developed tool is [www.mywindturbine.dk](http://www.mywindturbine.dk) (myWT)

A proper assessment of the energy yield of SWTs requires an analysis of wind turbine type and assessment of the available wind resources including the effect of local site characteristics, such as terrain and obstacles. To estimate the wind resource at the SWT position, long term wind data from the specific position is required (several years). However, to reduce the cost of wind resource assessments, myWT does not assess the wind resources by use of on-site wind measurements. Even though on-site wind measurements are the most reliable way of assessing the local wind resource, it is expensive and time-consuming, and the cost is not justified for SWTs. Instead, myWT uses large-scale meteorological computer models to estimate the general wind resource of an area and then applies a micro-scale flow model to estimate the effect of the local terrain and obstacles. Despite being more uncertain, models and topographical background data are at a level of quality that makes the calculated wind resources valuable for SWT projects. Having determined the wind resources, the second source of uncertainty in energy yield calculations is the wind turbine type or more specifically the power curve of the wind turbine. Many countries today have standards for how wind turbine manufacturers should collect and process data to produce certified power curves; this improves the accuracy of the power curves that could otherwise be too “optimistic”. However, small wind turbines are often installed under wind conditions far from the conditions specified in standards, and this is expected to lead to large power curve uncertainties.

This report evaluates the accuracy of myWT for calculation of the yearly energy yield also called the Annual Energy Production (AEP), using actual production data from some Danish wind turbines. The report does not aim at mapping the uncertainty of individual model components but simply compares the difference between the estimated and measured production. The validation starts with a short description of how the AEP calculations are performed in myWT (Section 3). This section describes the different computer models as well as the data used for the models. The report then presents the measured energy production data and explains how it

was long-term adjusted (Section 4). Finally, the model predictions and measurements are compared (Section 5), and conclusions are drawn (Section 6).

### 3. Energy Yield Calculations

This section gives an overview of the methodology used when the energy yield of SWTs are calculated using myWT. MyWT uses the Wind Atlas methodology (Troen & Petersen, 1989) implemented in the Wind Atlas Analysis and Application Program (WAsP). When the myWT-user selects a turbine location and a wind turbine generator, the following steps are made to calculate the annual energy production (AEP):

1. The pre-calculated generalised wind climate (Section 3.1) of the selected location is found in the myWT databases.
2. The site-specific topography (terrain elevation and roughness) of the selected location is found in the myWT database, and their impact on the wind is calculated using the IBZ micro-scale model (Section 3.2)
3. The obstacles (trees, hedges, and buildings) of the selected location are found in the myWT database and combined with user specified obstacles, and the wind sheltering effect they generate is estimated using the WAsP-Shelter obstacle model (Section 3.3)
4. Steps 1, 2 and 3 are combined to calculate the local wind climate at the SWT location, and the calculated local wind climate is applied to the SWT power curve to calculate the gross AEP (Section 3.4)
5. The net AEP can be estimated by specifying technical losses

#### 3.1 Generalised wind climate

Measuring on-site wind is usually the preferred method of understanding the wind resource at a specific location. However, this method is expensive and time-consuming since a minimum of 1-year on-site wind measurement data is required to avoid bias due to seasonal variations. Also, to minimise bias due to the interannual variability, the 1-year wind data need to be long-term adjusted using a long-term wind dataset. Small, affordable wind measurement systems exist, but the required measurement time, instrument uncertainties, and expertise required to apply long-term adjustments have led myWT to use another approach.

The approach selected by myWT is to use pre-calculated generalised wind climates of the wind atlas methodology (Troen & Petersen, 1989). A generalised wind climate consists of information of the wind direction distribution (wind rose) and wind speed distribution (Weibull distribution) of a (large) region. Traditionally, the generalised wind climates are calculated from measured wind data. However, in myWT, they are based on meteorological computer models (numerical wind atlas).

At the time of this report, two numerical wind atlases are available in myWT: 1) the Global Wind Atlas (2015) with global coverage and 2) a high-resolution dataset that covers Denmark only, based on the Weather Research and Forecasting (WRF) mesoscale model. The Global Wind Atlas generalised wind climates are provided by atmospheric reanalysis data, from meteorological centres around the world and have a resolution of about 50 km, while the WRF wind climate has a resolution of about 6 km. A description of how the WRF model was run can be found in Hahmann et al., (2014), while the method used to produce the generalised wind climates is described in Hahmann et al., (2015).



To generate the local wind climate for a specific wind turbine located in the region the next step is to calculate the site-specific topographical effects.

### 3.2 Topography Modeling

Hills and land cover (roughness) affect the wind flow; accelerating or decelerating the wind and possibly increasing the turbulence intensity. Since the generalised wind climate does not include local topographical effects, these effects are calculated using a microscale modelling system built into myWT.

In myWT, the topographical data (terrain elevation and roughness) covering the world is stored in a database. The database contains a global elevation dataset also used for the Global Wind Atlas (2015) that has a 3 arc-second resolution and is mainly based on data collected by the Shuttle Radar Topography Mission (SRTM). Denmark has a fine 5 m resolution elevation map. The global roughness data was also derived by the Global Wind Atlas and is based on data from the GlobCover 2009 land cover map. A large land cover extension in Denmark is “cropland,” which has been assigned the roughness value of 0.3 m.

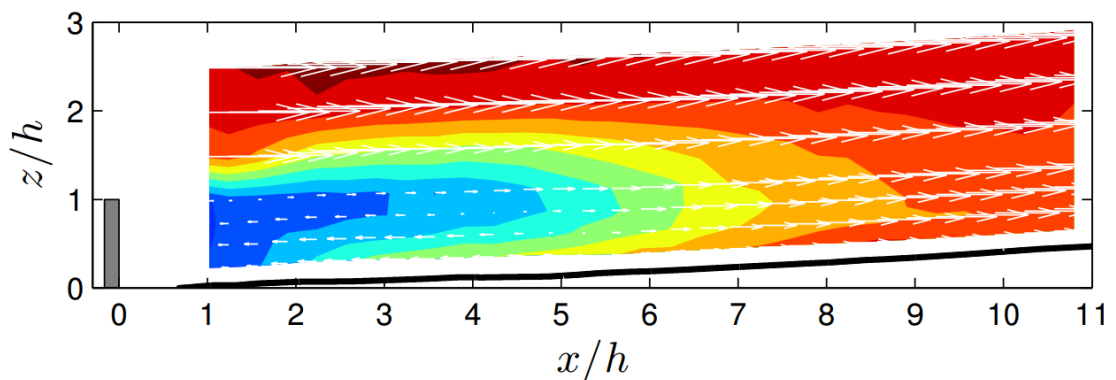
To calculate the speed change due to topography myWT utilises the IBZ-model of Troen (1990) also used in the Wind Atlas Analysis and Application Program (WAsP) by Troen and Petersen (1989) and the site-specific topography effects are applied to the generalised wind climate.

### 3.3 Obstacle Modeling

In addition to topography, the wind flow may also be influenced by sheltering obstacles. Obstacles such as trees, forest, hedges, fences and buildings shelter or “shadow” the wind and can significantly reduce the annual energy yield of wind turbines. For large wind turbines, the sheltering effect often only plays a small role as the turbines are often placed in open, shelter-free, areas and with hub heights beyond the height influenced by the obstacles. SWTs, however, are often placed close to houses and trees and with hub heights within the height influenced by the obstacles. Therefore, obstacles can significantly reduce the AEP of SWTs. Therefore, obstacles need to be considered carefully before installing domestic wind turbines.

As an illustration of the influence of obstacles, Figure 1 below shows measurements of the sheltering effect behind a 3 m tall and 30 m wide fence by Peña et al. (2015). As seen in the Figure, the sheltering effect is clearly visible up to 30 m behind the fence (10 times the height of the fence) and also above the height of the fence. SWTs are often placed in comparable locations and myWT can take these sheltering effects into consideration.

In myWT, the model that calculates the sheltering effect behind obstacles is called “WAsP-Shelter”, and an analysis of the model error is found in Peña et al. (2015). The wind flow behind obstacles such as houses and trees is further turbulent and complicated to describe and model. It depends on the exact geometry of the obstacle, and how the obstacle “interacts” with the wind; a tree that bends in the wind has a different sheltering effect than that of a solid building or fence. WAsP-shelter simplifies the description of an obstacle to 3 parameters: 1) The outer shape of the obstacle, 2) its height, and 3) its “porosity”, which is a value between zero and one (0 for “buildings”, 0.1 for “dense forest” and 0.4 for “light forest”).



*Figure 1: Mean wind speed behind a fence compared to the undisturbed wind. Dark red corresponds to undisturbed wind while dark blue means that the wind has been fully slowed down. The Figure is from Peña et al. (2015)*

myWT includes data for most obstacles in Denmark. These are based on shapefiles released by the Danish “Geodatastyrelsen”, given additional information of height and porosity. Since obstacles change in time (e.g. trees grow, and new buildings are constructed), the users of myWT can manually change the obstacle data from myWT as they see appropriate. We expect that users often have a knowledge of the obstacles near the wind turbine, which they can use to make improved AEP calculations. To make an objective evaluation of the model, this report presents two types of calculations:

1. myWT: Calculations with the standard obstacle data and with user improvements
2. WAO: Calculations with the standard obstacle data only, without user improvements

We expect that “myWT” results are more accurate than “WAO” since the geometry of the obstacles has been improved.

The WASP-shelter model is based on a mathematical expression calibrated for 2D obstacles (see Eq. 22 in Peña et al. (2015)). As demonstrated in the fence experiment and by Taylor and Salmon (1993) the expression has a tendency to overestimate the sheltering effect in the far wake region for 3D obstacles. Because of this, WASP-shelter has been recalibrated specifically

for myWT and the obstacle types contained in myWT. For the calibration, the production yield from 19 SWTs (WT 7 was excluded, see section 5.1) was estimated using the standard obstacle data (WAO setup) and the constant,  $Ch$ , (Peña et al. 2015) was varied from the standard value of 0.8 recommended for 2D obstacles. Figure 2 shows how the mean production is underestimated when  $Ch = 0.8$  and overestimated for  $Ch = 0.4$ . Using  $Ch = 0.6$  the estimation bias is removed; we, therefore, use that value for myWT and in all subsequent analysis.

### 3.4 Annual Energy Production

After the adjusted wind climate is determined, the gross AEP is calculated by applying the wind turbine power curve provided by the wind turbine manufacturer. The power curve expresses the wind turbine power output as a function of wind speed. Traditionally, wake losses need to be subtracted from the gross AEP to estimate the net AEP, but since myWT is only designed for calculating the AEP of single wind turbines, wake losses are not considered.

Wind turbines - and especially SWTs - are greatly affected by the turbulence intensity of the wind and can, therefore, underperform compared to the certified power curves used in the myWT calculations. Also, different technical and operational losses exist that reduce the AEP. In myWT, the technical losses can be specified and subtracted from the gross AEP to estimate the net AEP. However, in this report, we adjust the measured production from technical losses and compare gross AEPs.

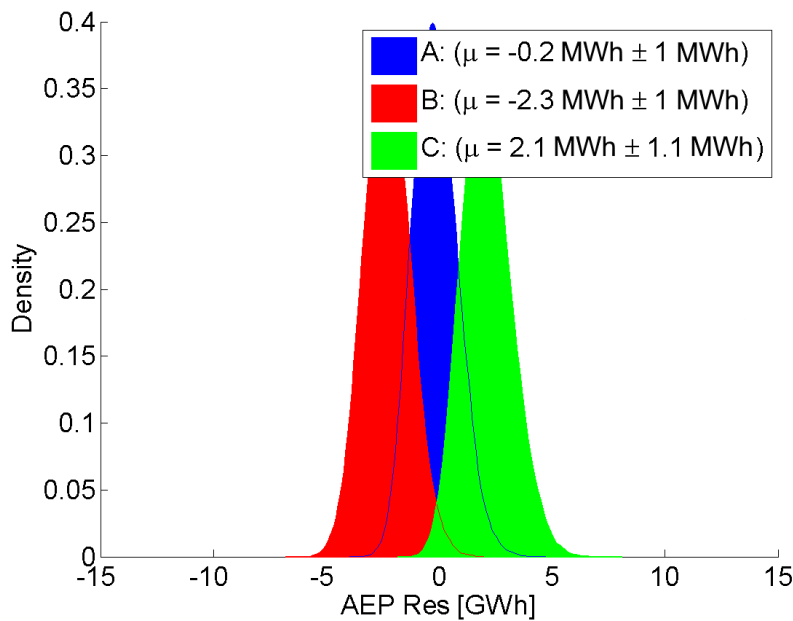


Figure 2: The Figure shows the mean bias ( $\mu$ ) of the gross AEP for WAO calculations. 19 wind turbines were used in the calculations (WT 7 was excluded). Different values of  $Ch$  were used. A:  $Ch = 0.6$ , B:  $Ch = 0.8$ , C:  $Ch = 0.4$ . For  $Ch = 0.6$  the bias has been reduced to  $\mu = -0.2$  MWh. The uncertainty of the bias ( $\text{std} \approx 1$  MWh) is found using a bootstrapping method.

## 4. Energy Yield Data

The wind energy production data used in this report come from private wind turbine owners as well as wind turbine manufacturers. All turbines are grid connected and owned by private individuals to reflect market realities as well as possible. In total, data from 20 SWTs has been collected. The SWTs are produced by four different manufacturers (3 Danish and 1 foreign) with generators ranging between 10 and 25 kW, hub heights between 18 m and 21 m, and different rotor areas; however, all are restricted to a tip height of 25 m. The manufacturers of the individual SWTs are kept confidential, but graphics in appendix give an impression of the natural environment of each turbine.

In Denmark, there is an open national “Stamdata” database made by the Danish Energy Agency that consists of energy production data from all operational and decommissioned wind turbines registered in Denmark. Stamdata would have the energy production stored in Stamdata is the measured energy fed into the electrical grid; the turbine operators own consumption is not recorded. For SWTs this is often a large part of the total energy production and would add too much uncertainty to the validation. Therefore, Stamdata was not used in the present study and the validation results presented are based on only 20 SWTs.

### 4.1 Long-term adjusting of energy production data

Due to the variability of the wind, the energy production from an SWT can change significantly from year to year. Since myWT estimates the 20-year mean annual energy production (AEP), one cannot directly compare this to the yearly fluctuating net production from an SWT. To make comparisons, the measured energy production has been long-term adjusted using the Danish Wind Energy Index (DK Index, [www.vindstat.dk](http://www.vindstat.dk)). To ensure proper long-term adjustment, priority has been placed on using SWT data with several years of energy production data. Table 1 gives an overview of the months of data available, the long-term adjusted AEP, and the yearly standard deviation for each SWT. The standard deviation indicates the accuracy of the long-term AEP for each SWT. For most of the SWTs, monthly energy data was available, but others only had yearly values. Long-term adjustments were applied to the source data i.e. on the monthly or yearly data.

To adjust energy production data for wind turbine availability and technical losses, months with particularly low SWT productions compared to the DK index were disregarded. Also, when wind turbine availability was provided, it has been used to estimate the gross AEP. The long-term adjusted AEP of Table 1 was, therefore, at least partly, adjusted for wind turbine availability, so that they are comparable to the gross AEP calculations from myWT. The estimated AEP for the 20 SWTs is also shown in Figure 3.

### 4.2 Energy production variability

As seen in Table 1 and Figure 3 the SWTs have AEP values between 3 and 82 MWh. In the mean, the turbines produce 33.9 MWh with a standard deviation of 17.1 MWh. Without any knowledge of local wind conditions or tools to help estimate the production, this very uncertain AEP estimate would be the only one available for future SWTs of similar type. For electricity consumers, the price of 1 MWh in Denmark is presently about 2.500 DKK. Assuming that the 20

SWTs are representative for SWTs in Denmark, the mean yearly production value is therefore about  $85000 \pm 43000$  DKK. This is surely too uncertain to make an SWT investment decision.

*Table 1: The measured and long-term adjusted gross AEP of the 20 SWTs used in the validation study. “Data” are the number of months of data. “AEP” is the gross AEP. “ $\sigma_{AEP}$ ” is the coefficient of variation (standard deviation) of AEP.*

<b>Wind Turbine</b> [#]	<b>Data</b> [months]	<b>AEP</b> [MWh]	<b><math>\sigma_{AEP}</math></b> [MWh]	<b><math>\sigma_{AEP}</math></b> [%]
1	36	25.4	1.6	6
2	36	38.6	4.7	12
3	24	36.0	2.5	7
4	24	43.1	1.0	2
5	24	38.6	0.1	0
6	24	44.1	1.3	3
7	24	81.6	0.4	1
8	24	25.2	3.0	12
9	12	62.9	-	-
10	84	39.0	1.9	5
11	24	37.9	2.2	6
12	24	3.3	-	-
13	24	12.0	-	-
14	24	20.6	1.5	7
15	24	26.6	2.7	10
16	24	19.0	2.2	12
17	12	25.9	-	-
18	12	32.5	-	-
19	12	27.3	-	-
20	12	37.7	-	-
<b>Mean</b>	<b>25</b>	<b>33.9</b>	<b>1.9</b>	<b>6.4</b>
<b>Std. deviation</b>		<b>17.1</b>	<b>-</b>	<b>-</b>

### Measured AEP ( $\mu = 33.9 \text{ GWh} \pm 17.1 \text{ GWh}$ )

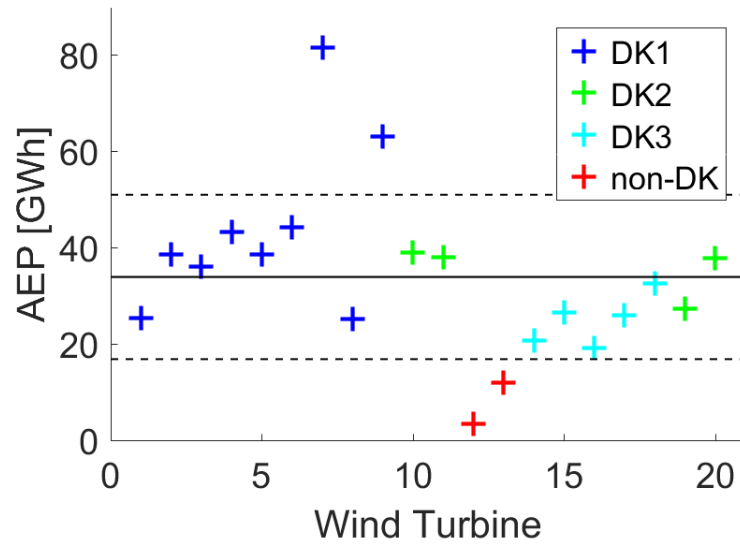


Figure 3: Measured and long-term adjusted AEP for the 20 wind turbines used in the validation study. The mean AEP (33.9 MWh) and the standard deviation (17.1 MWh) is indicated by a solid and dashed lines.

## 5. Evaluation of Energy Yield Calculations

In this section, the calculated AEP of myWT (section 3) is evaluated against the measured AEP (section 4). Throughout the section two sets of calculated AEPs are presented: myWT and WAO results. myWT results are made using the web page [www.mywindturbine.com](http://www.mywindturbine.com). For the myWT results, the sheltering obstacles suggested by myWT have in some cases been manually modified if we subjectively evaluate that they do not accurately describe reality. The WAO calculations, however, have been made automatically using the standard obstacle dataset without any manual improvements. So the WAO calculations represent results a non-experienced myWT user can expect.

### 5.1 Wind Turbine Production Estimates

Table 2 shows the calculated AEPs for the 20 SWTs. As seen, the mean AEP for both myWT (33.5 MWh) and WAO (32.5 MWh) is close to the mean value of the measurements (33.9 MWh); this is no surprise as the bias was removed by the WAsP-shelter calibration (Section 3.3). The spread of the model predictions (13.2 and 12.8 MWh) is somewhat lower than measured (17.1 MWh); indicating that myWT does not include the full range of real variability.

*Table 2: Calculated AEP. “myWT” is the gross AEP calculated using [www.mywindturbine.com](http://www.mywindturbine.com). “WAO” is a fully automatic AEP calculation. The measured AEP is repeated from Table 1.*

Wind Turbine [#]	MyWT [MWh]	WAO [MWh]	Measure [MWh]
1	37.0	37.6	25.4
2	38.1	36.4	38.6
3	33.3	30.8	36.0
4	45.1	43.5	43.1
5	42.6	40.8	38.6
6	43.0	42.3	44.1
7	60.5	58.5	81.6
8	32.6	32.7	25.2
9	60.3	59.4	62.9
10	37.1	34.1	39.0
11	35.2	34.0	37.9
12	6.4	6.4	3.3
13	11.9	11.3	12.0
14	20.9	20.4	20.6
15	25.4	24.6	26.6
16	22.5	22.1	19.0
17	23.9	23.1	25.9
18	28.9	28.4	32.5
19	29.9	29.4	27.3
20	34.6	34.7	37.7
<b>Mean</b>	<b>33.5</b>	<b>32.5</b>	<b>33.9</b>
<b>Std. deviation</b>	<b>13.2</b>	<b>12.8</b>	<b>17.1</b>

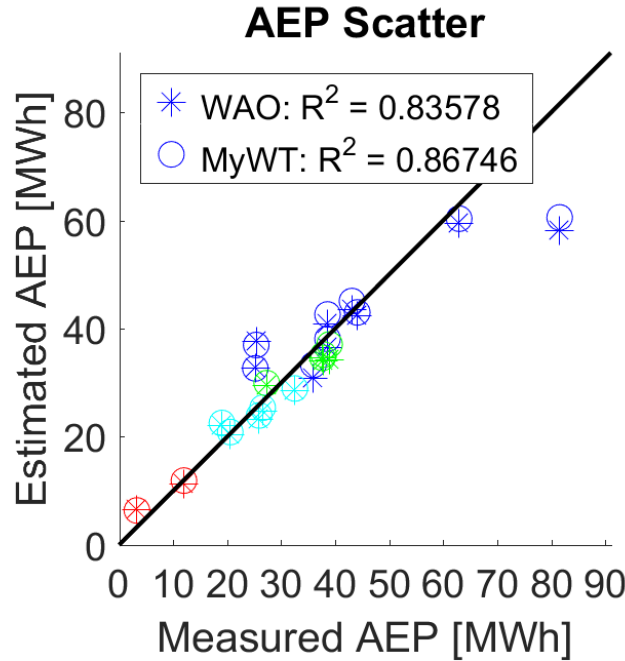


Figure 4: The correlation between the measured and estimated AEP is shown. The colours indicate the different wind turbine types (same as Figure 3), the line represents a 1:1 relation.

Figure 4 shows a scatter plot, indicating the correlations between calculations and measurements. As expected, myWT has a higher correlation coefficient than WAO showing that experienced users can achieve less uncertain AEP calculations. As it is also seen, SWT number 7 (SWT7) stands out among the others wind turbines in Figure 4. The measured AEP is an impressive 81.6 MWh, but the myWT and WAO models only predict 60.5 and 58.5 MWh, respectively. As this turbine has no sheltering obstacles for westerly winds (the main wind direction), the under-prediction of the AEP can only be explained by the generalised wind climate used at this location (section 3.1). SWT7 is located on the west coast of Denmark, close to the North Sea, and it appears that the large-scale WRF model used to estimate the wind climates has missed the exact water-to-land transition at this location. Due to the large under-prediction ( $\sim 26\%$ ) of SWT7, this turbine was not included for calibration of WAsP-shelter (section 3.3). The coefficient of determination increases to  $R^2 = 0.91$  for the myWT estimations if SWT7 is excluded, however, it is included in the following analysis.

## 5.2 Calculation Error

In Figure 5, the AEP calculation error is shown for all SWTs. As indicated, the myWT AEP calculation error has a slight negative bias,  $\mu = -0.4$  MWh, with a standard deviation of  $\sigma = \pm 5.8$  MWh. If SWT7 was excluded the standard deviation would drop to  $\sigma = \pm 3.8$  MWh. Figure 6 also shows the AEP calculation error but as a function of the measured AEP. As seen, there does not seem to be a correlation between measured AEP and the AEP error. The AEP relative error (in percentage) is, therefore, large for low-producing turbines and relatively low for high-producing turbines.



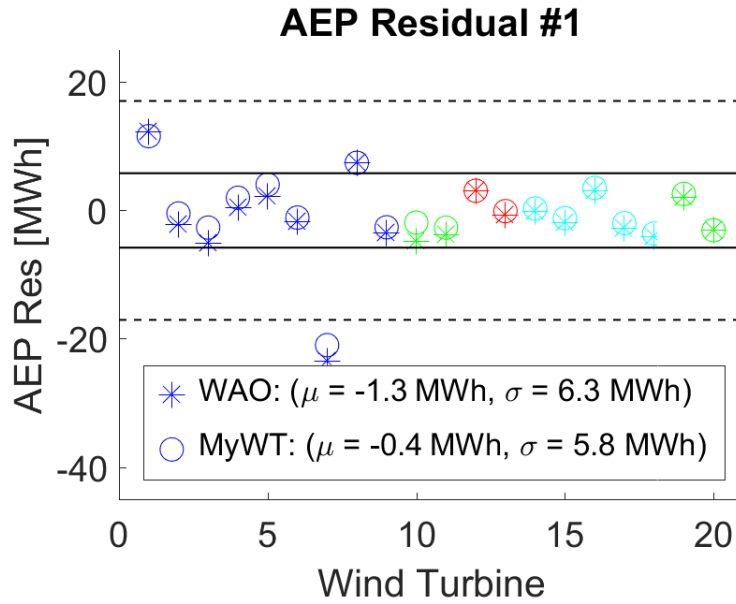


Figure 5: AEP calculation error for all 20 SWTs using the same colour coding as figure 3. The dashed lines indicate the standard deviation of the measured AEPs ( $\pm 17.1$  MWh) while the solid line indicates the standard deviation of the AEP errors of myWT ( $\pm 5.8$  MWh).

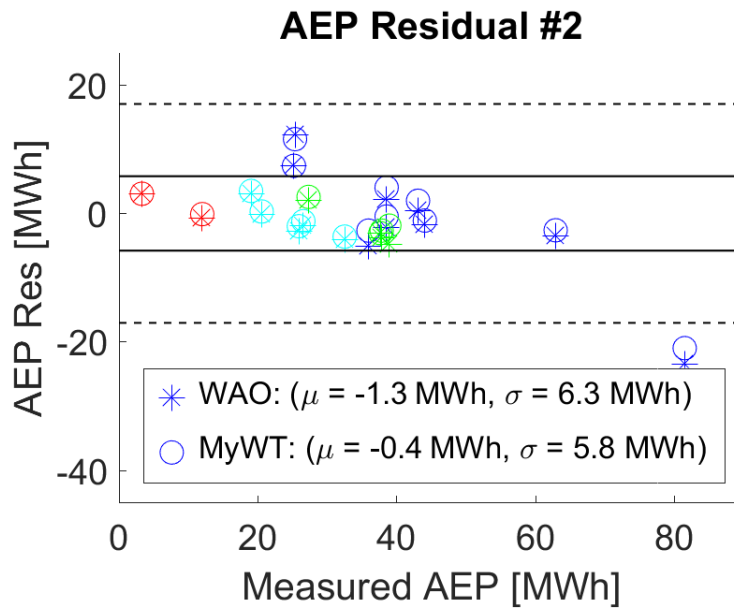


Figure 6: AEP calculation error for all 20 SWTs using the same colour coding as figure 3. The dashed lines indicate the standard deviation of the measurements ( $\pm 17.1$  MWh) while the solid line indicates the standard deviation of the AEP calculation error of myWT ( $\pm 5.8$  MWh).

Both Figure 5 and 6 indicate with solid and dashed lines the standard deviation of the AEP calculation error for the myWT calculations ( $\sigma = \pm 5.8$  MWh) and the standard deviation of the measured AEP ( $\sigma = \pm 17.1$  MWh). The lines illustrate how the uncertainty is reduced by using a model like myWT compared to only having knowledge of measured AEP for existing SWTs. Without any prior wind-assessments the best production “guess” for a small wind turbine of a

similar type as analysed in this report would be 33.9 MWh with a standard deviation of 17.1 MWh; if the production value from myWT is used instead, then the standard deviation drops to 5.8 MWh.

There is a 50% probability that the actual production will exceed the estimate from myWT, such estimation is therefore often denoted as P50. To reduce the risk of investment, the SWT investor can be interested in a more conservative AEP estimate. The P90 is the AEP estimate which has a 90% probability of being exceeded and therefore has less associated risk compared to P50 when making SWT investments. Since the AEP calculation error seems independent of the actual production (see Figure 6) the P90 from myWT can be estimated as,  $P90 = P50 - 1.28 \sigma_{AEP} = P50 - 7.4 \text{ MWh}$  (assuming the probability distribution of the turbine production to be Gaussian distributed).

We use a bootstrapping method to investigate the uncertainty on the AEP calculation error bias and of the standard deviation of the AEP calculation error. In other words, we want to investigate how much the presented results can be trusted when the sample size is only 20 SWTs. The results of the bootstrapping exercise are presented in Figure 7. The left of Figure 7 shows that the bootstrapping procedure predicts that the standard deviation of the mean AEP calculation error is 1.4 MWh for the myWT results; meaning that the predicted bias of the myWT is  $-0.4 \pm 1.4 \text{ MWh}$ . To the right of Figure 7, it is seen that standard deviation of the AEP calculation error is  $5.8 \pm 1.8 \text{ MWh}$ . There are therefore some important uncertainties associated to model validations presented in this report, due to the limited sample size of 20 SWT.

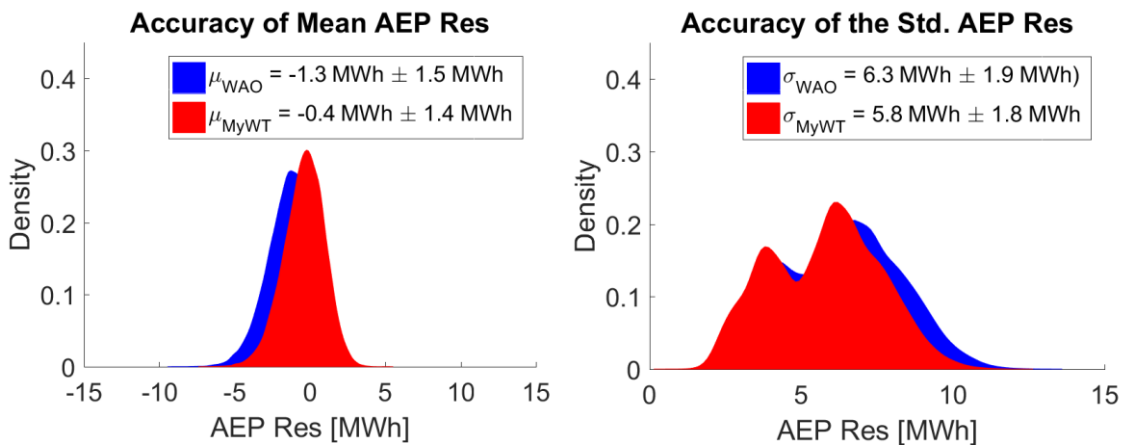


Figure 7: The figure shows the uncertainty on the mean bias ( $\mu = -0.4 \pm 1.4 \text{ MWh}$ ) and of the standard deviation of the AEP calculation error ( $\mu = 5.8 \pm 1.8 \text{ MWh}$ ) due to the limited sample size of 20 SWTs used in this report. To the right, we see that the resampling procedure does not achieve a Gaussian distribution, suggesting that a larger sample size would be useful to complete the bootstrapping procedure.

## 6. Summary & Conclusions

In this report energy yield calculations of 20 small wind turbines (SWT) located in Denmark were compared to measured energy yields, with the purpose of evaluating the accuracy of [www.mywindturbine.com](http://www.mywindturbine.com) (myWT).

The data sources used by myWT are different and presumably better in Denmark (and in the UK) compared to the rest of the world. Therefore, the conclusions of this report are only valid for this region. Similar comparisons for other parts of the world are recommended.

The SWT types investigated were all similar, with wingtip heights of 25 m, generator sizes of around 10 kW and were freestanding, mounted on a tower placed in a relatively open country site (but within 20 m of a farm house). The findings in this report are therefore not valid for micro wind turbines that are building-mounted or located in urban environments.

Based on the measured energy yield from 19 of the 20 SWTs, WAsP-shelter was, as expected, shown to overestimate the sheltering effect of real 3D obstacles. The bias error was removed by recalibrating the model.

The energy yield of SWTs is greatly affected by the local environment. Even though all SWTs in this report had certified power curves, and were placed in a relatively open countryside, the variations in energy yield were very large (the standard deviation of AEP was more than 50%). SWT investments without any prior AEP assessment is surely an ill-advised gamble.

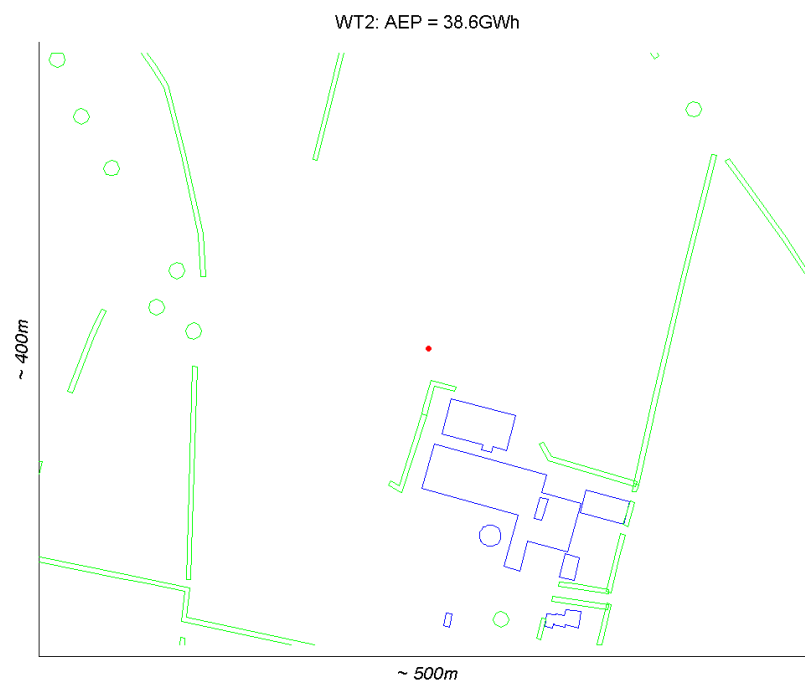
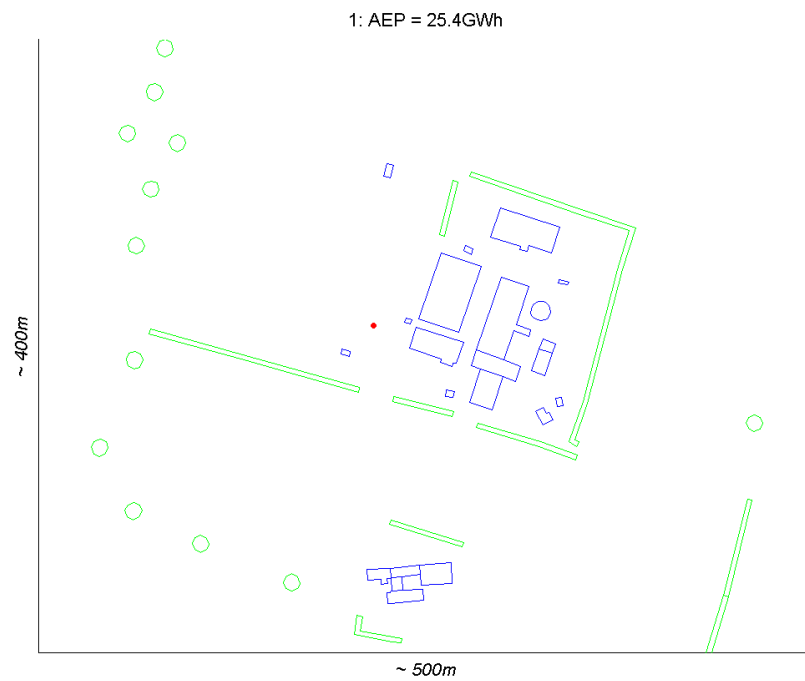
MyWT offers the possibility to make AEP assessments for SWTs and greatly decreases the investment risk (the standard deviation of the AEP error dropped from 17.1 to 5.8 MWh). To some extent, the calculation error of myWT was shown to be independent of the AEP. The AEP uncertainty is therefore relatively small for SWTs with large AEPs and large for SWTs with small AEPs. Careful users, can therefore potentially use myWT to sort good SWT investments from bad ones.

## References

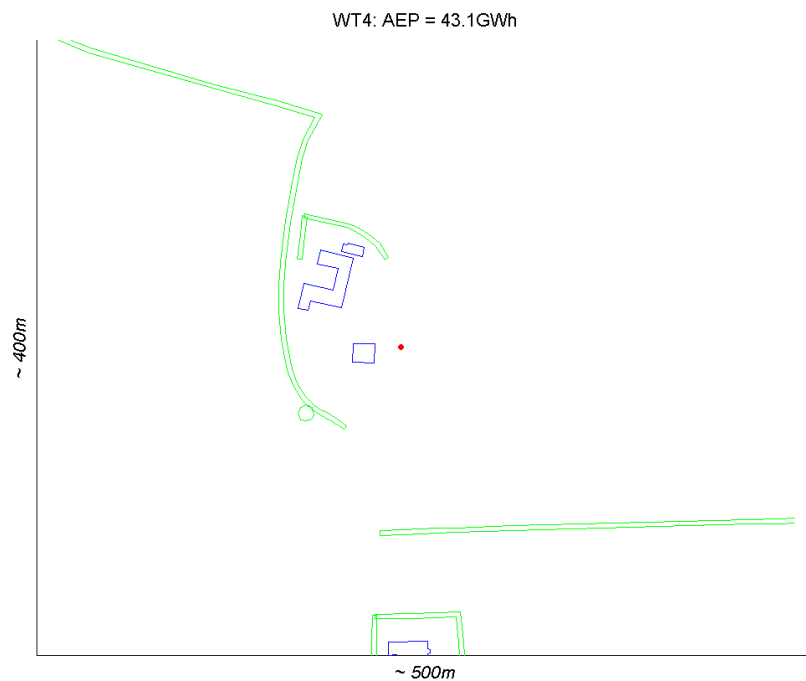
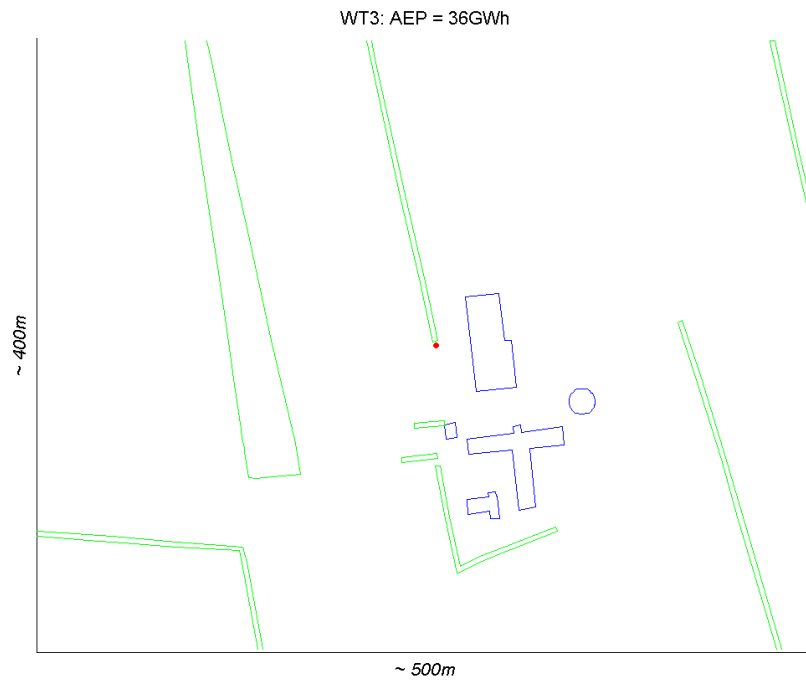
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# Appendix

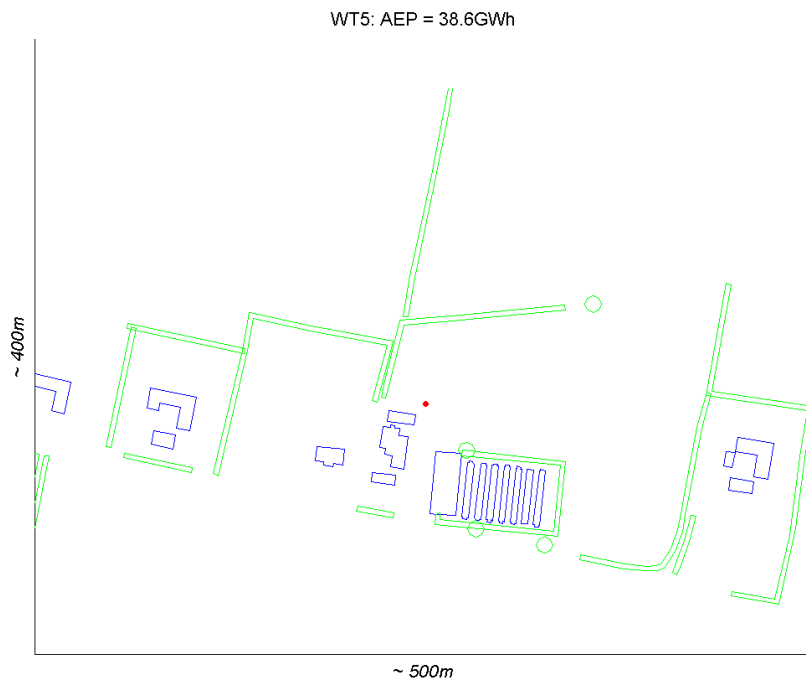
## Obstacles nearby the SWTs



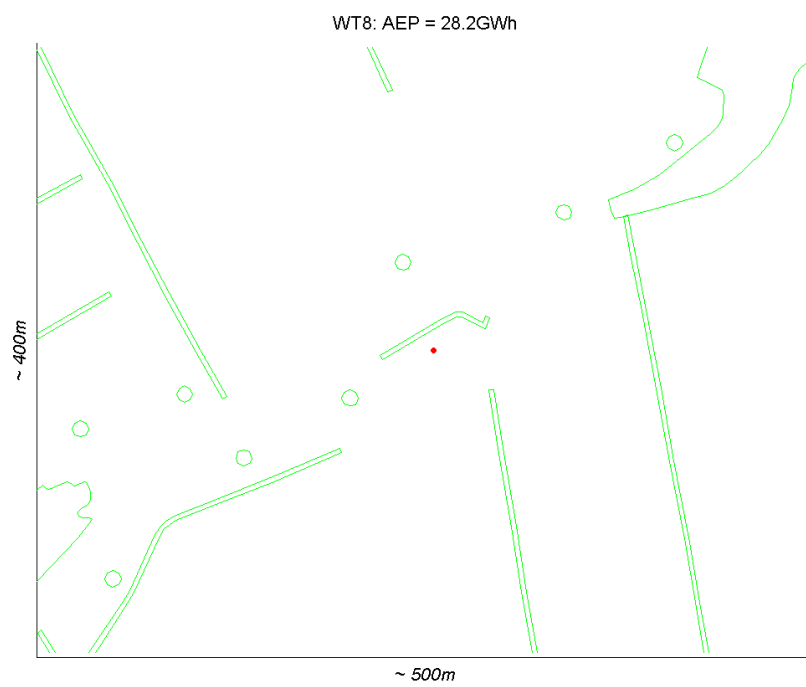
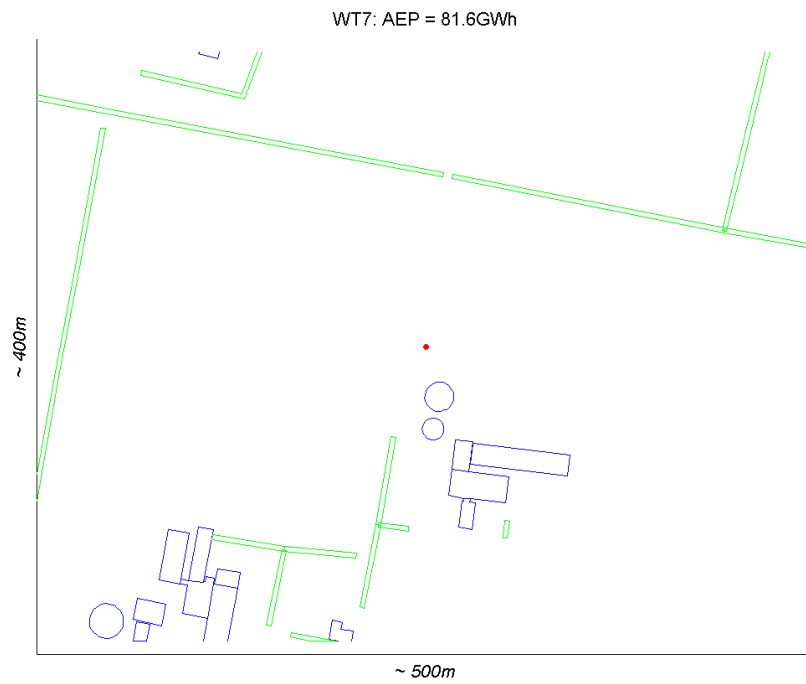
The nearby environment of turbine 1 (top) and turbine 2 (bottom). Green indicate vegetation, blue is buildings and red is the turbine location



The nearby environment of turbine 3 (top) and turbine 4 (bottom). Green indicate vegetation, blue is buildings and red is the turbine location

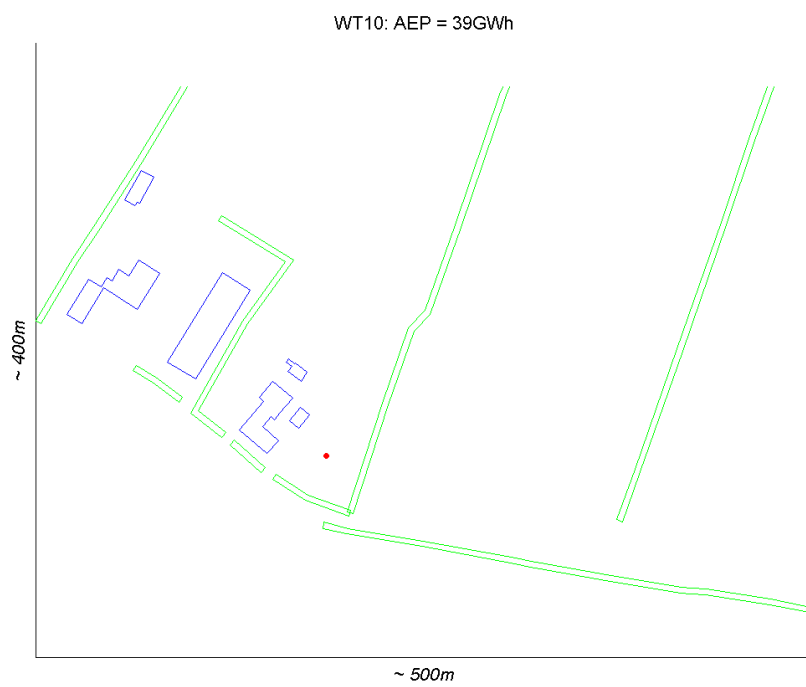
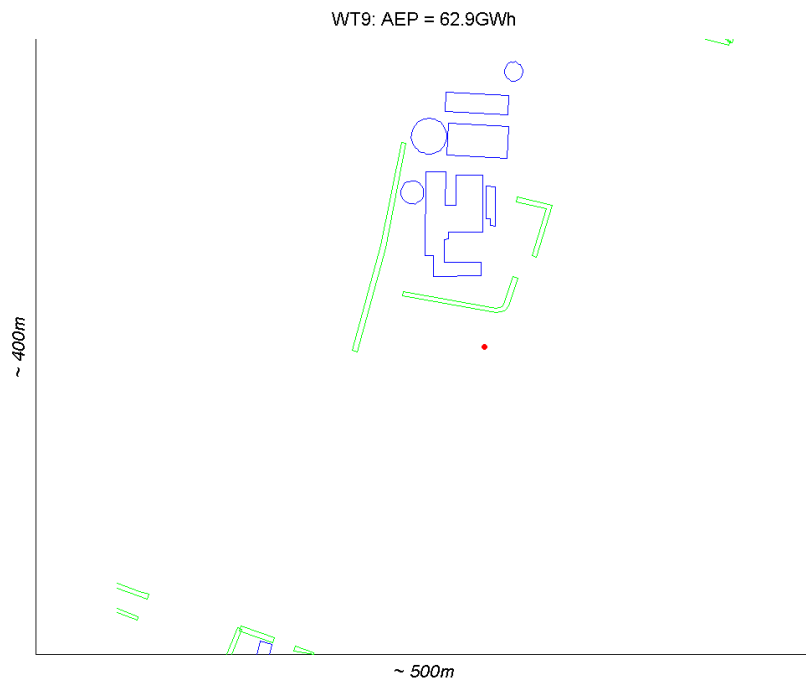


*The nearby environment of turbine 5 (top) and turbine 6 (bottom). Green indicate vegetation, blue is buildings and red is the turbine location*

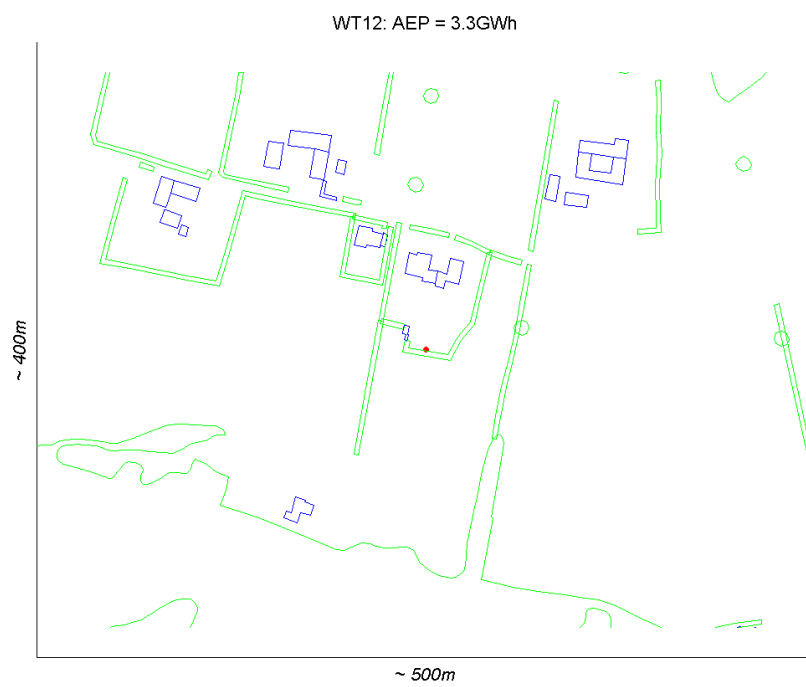
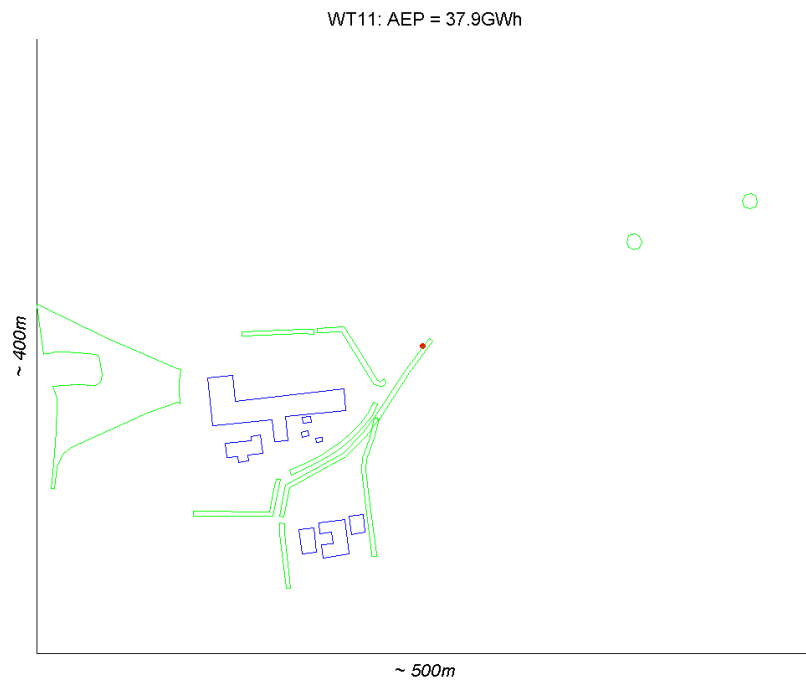


*The nearby environment of turbine 7 (top) and turbine 8 (bottom). Green indicate vegetation, blue is buildings and red is the turbine location*

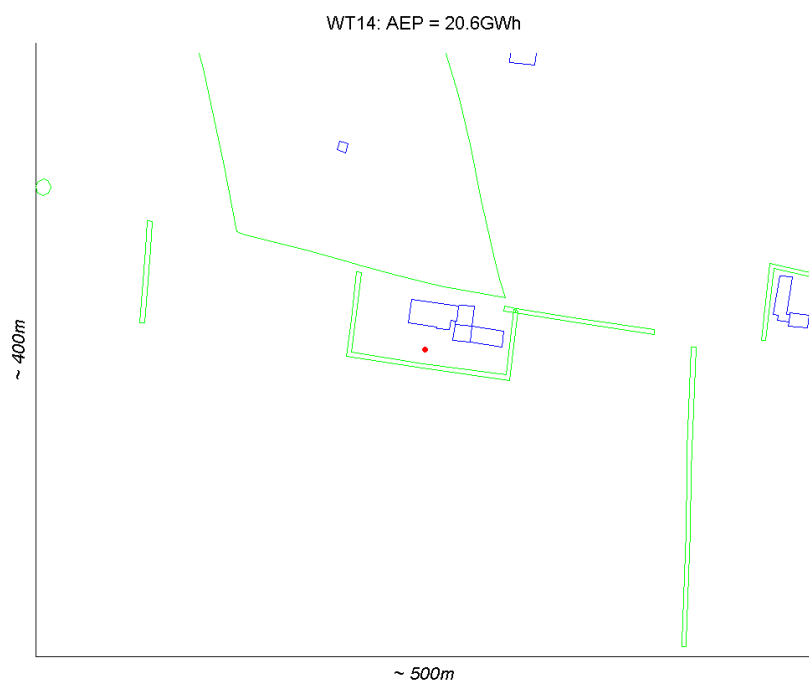
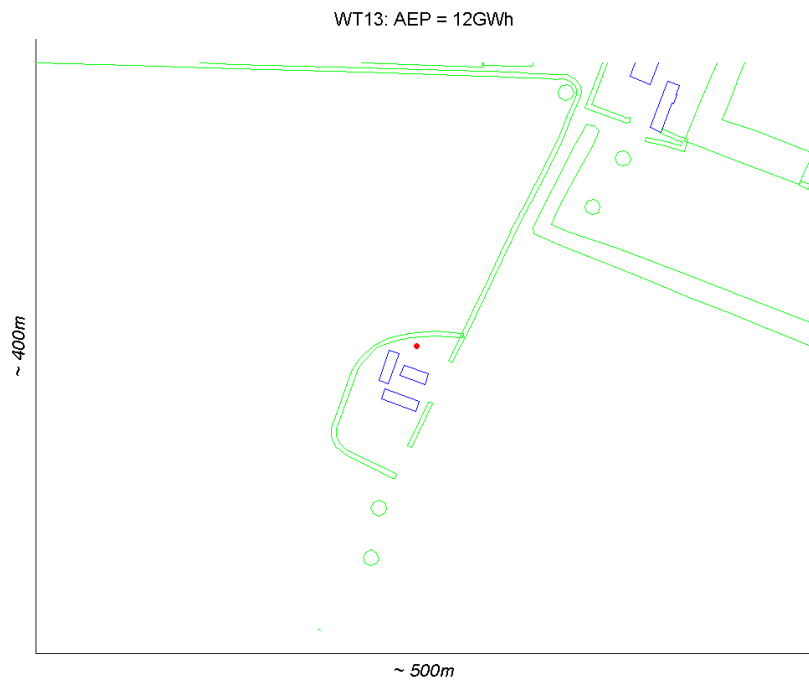




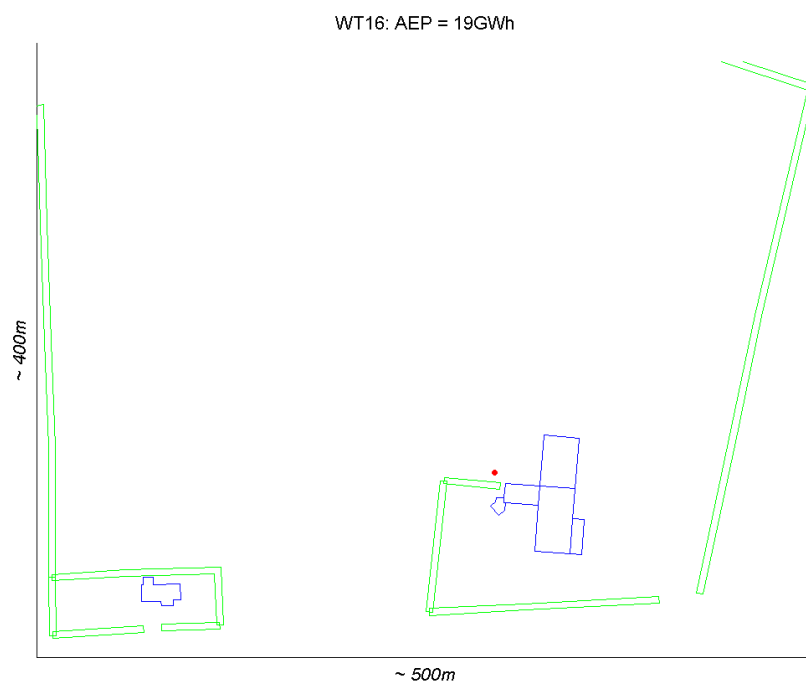
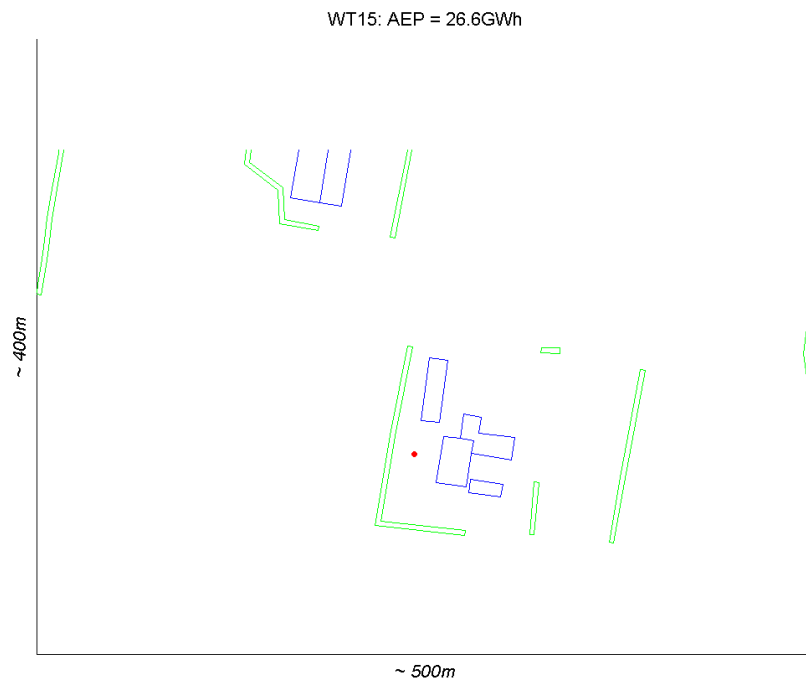
*The nearby environment of turbine 9 (top) and turbine 10 (bottom). Green indicate vegetation, blue is buildings and red is the turbine location*



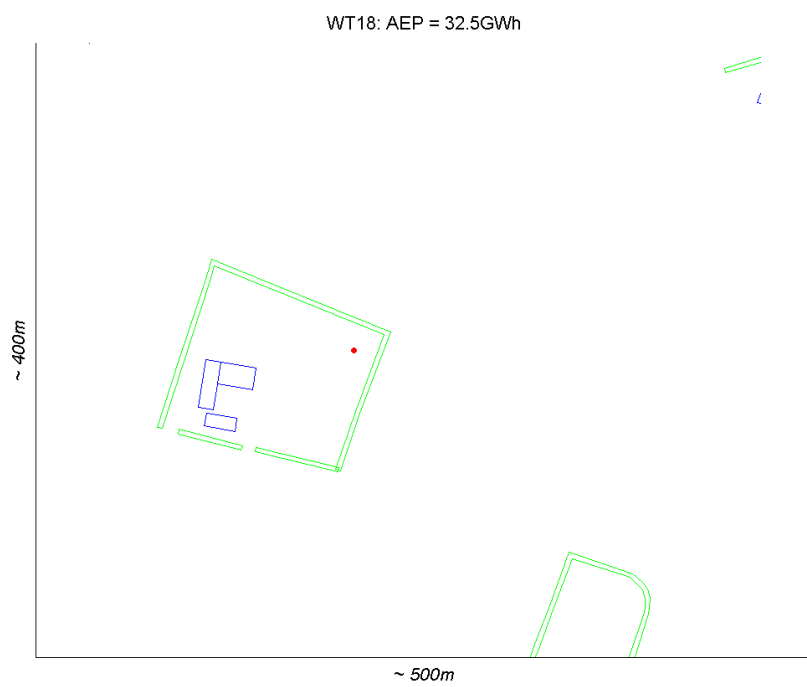
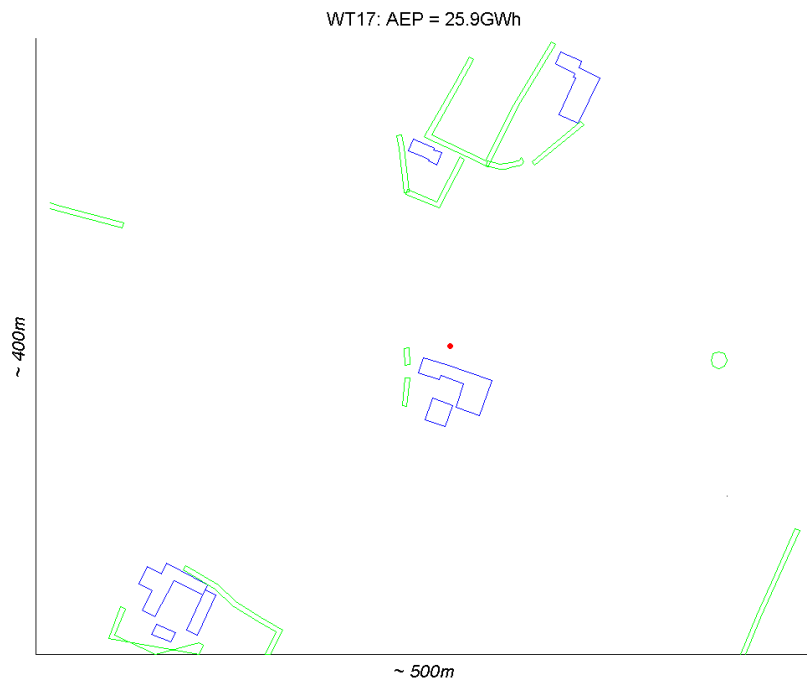
*The nearby environment of turbine 11 (top) and turbine 12 (bottom). Green indicate vegetation, blue is buildings and red is the turbine location*



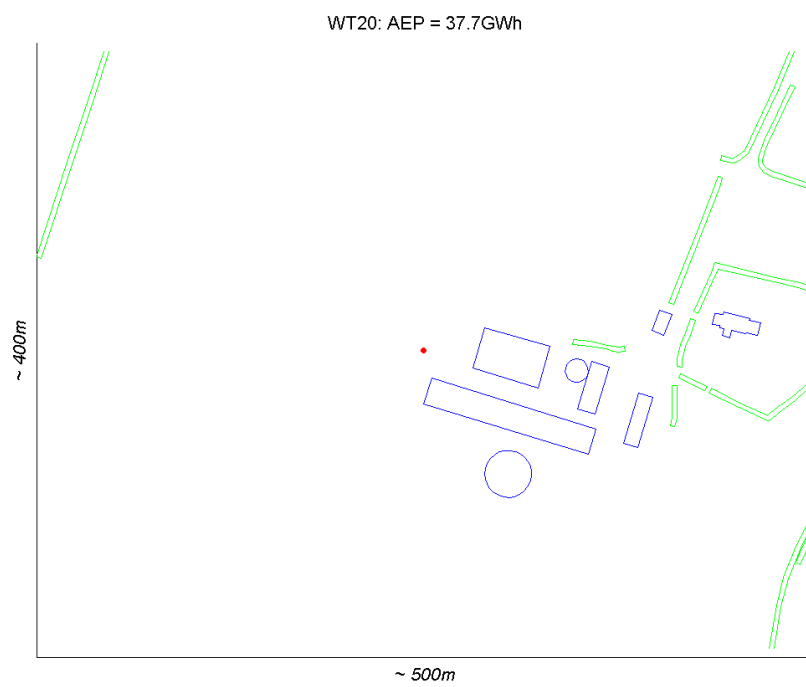
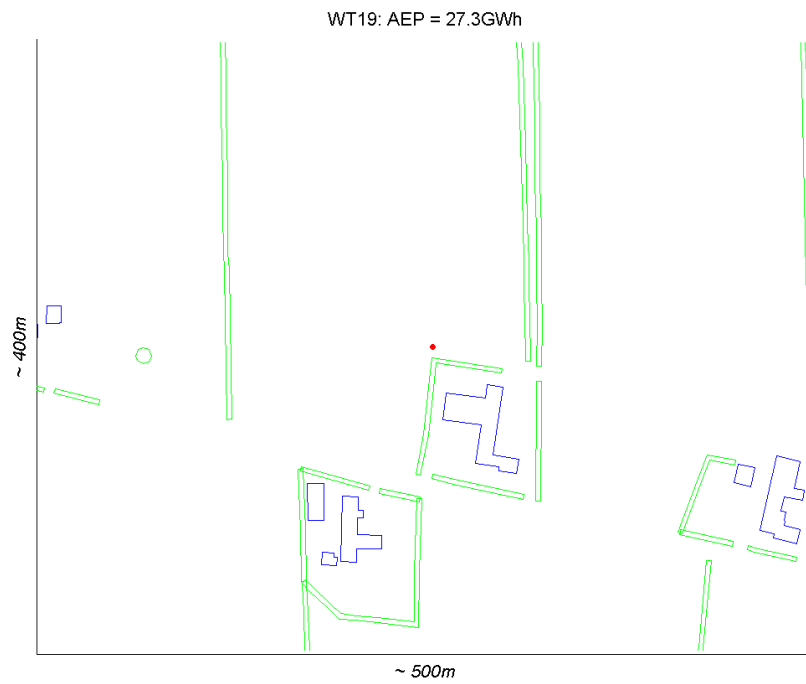
*The nearby environment of turbine 13 (top) and turbine 14 (bottom). Green indicate vegetation, blue is buildings and red is the turbine location*



*The nearby environment of turbine 15 (top) and turbine 16 (bottom). Green indicate vegetation, blue is buildings and red is the turbine location*



*The nearby environment of turbine 17 (top) and turbine 18 (bottom). Green indicate vegetation, blue is buildings and red is the turbine location*



*The nearby environment of turbine 19 (top) and turbine 20 (bottom). Green indicate vegetation, blue is buildings and red is the turbine location*

# Acknowledgements

## **EUDP**

This report has been done as part of the EUDP project "OnlineWAsP for mellemstørrelses vindmøller" Journal number 64013-0512. The financial support is greatly appreciated.

## **EMD International A/S**

EMD are myWT-project partners and their expertise in wind farm planning and development of windPRO software has been invaluable for the development of myWT.

## **World in a Box**

The software development team at WIAB has been a key component for the successful completion of the myWT-project. WIAB uniquely manages to bridge the gap between science and software

DTU Vindenergi er et institut under Danmarks Tekniske Universitet med en unik integration af forskning, uddannelse, innovation og offentlige/private konsulentopgaver inden for vindenergi. Vores aktiviteter bidrager til nye muligheder og teknologier inden for udnyttelse af vindenergi, både globalt og nationalt. Forskningen har fokus på specifikke tekniske og videnskabelige områder, der er centrale for udvikling, innovation og brug af vindenergi, og som danner grundlaget for højt kvalificerede uddannelser på universitetet.

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